

INFRASTRUCTURE MANAGEMENT AND ENGINEERING

**INVESTIGATION OF PAVEMENT CRACKING ON SR-4 AND  
DEMONSTRATION OF THE MULTI-HEAD BREAKER  
IN FRACTURING REINFORCED CONCRETE PAVEMENTS  
BEFORE ASPHALT OVERLAY**

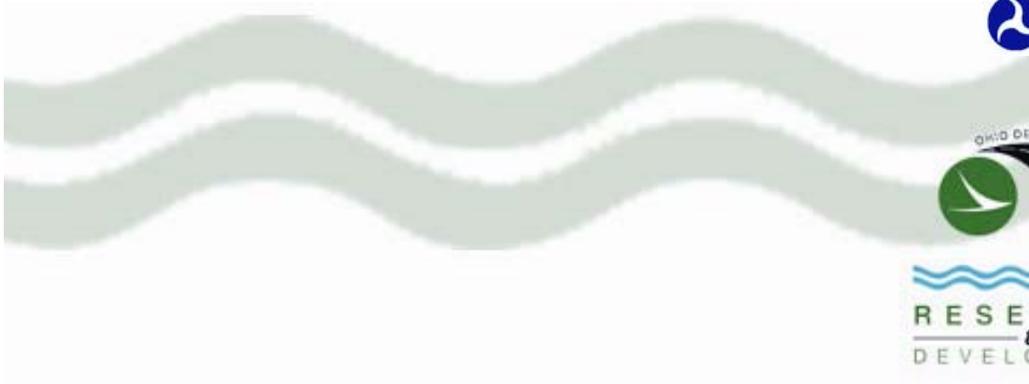
Final Report

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## **DISCLAIMER**

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16. Abstract: <p>This report presents the details of a study conducted by Infrastructure Management and Engineering (INFRAME) to review condition of selected break and seat (B/S) and rubblization projects constructed by Ohio Department of Transportation (ODOT), and also to demonstrate the ability of various pavement breakers to produce desired breaking patterns and fractured particle sizes required by ODOT specifications. A program of field evaluations was undertaken on four test projects. The pavement on SR-4 was rehabilitated in 1993 by breaking the underlying jointed reinforced concrete pavement with a pile hammer prior to constructing an asphalt overlay. The pavement on SR-36 project was rehabilitated in 1992 by rubblizing the existing jointed concrete pavement with a Resonant Pavement Breaker (RPB) and constructing an asphalt overlay. The continuous concrete pavement on I-70 was rubblized in 2005 with a Multi Head Breaker (MHB), in preparation for an initial asphalt overlay. On the I-71 project, MHB was used to demolish the existing jointed reinforced concrete pavement and demonstrate the capabilities of MHB to produce various fracturing patterns.</p> <p>At each test site, a test pit was dug and a visual assessment of the condition of the fractured pavement overlay and subbase/subgrade was made. Measurements were made of the fracturing pattern at the surface of the concrete and gradation tests were performed to determine the particle size distribution at various depths within the fractured slab. Deflection tests were performed to determine the effect of the observed breaking patterns on the stiffness of the pavement layers. Examination of test pit material indicated that the pile hammer used in constructing the B/S sections on the SR-4 project did not provide the vertical through cracking and steel debonding required by the project specifications. Despite this, the overlay on the B/S section provided vastly superior reflection crack performance than the untreated control section. The MHB equipment used on I-70 appeared capable of providing the breaking patterns and particle sizes required by ODOT specifications. However, the MHB equipment used on I-71 by a different contractor did not produce the desired results; a significant amount of large, un-cracked pieces were observed particularly below the reinforcing steel, regardless of desired breaking pattern. On the other hand, the Resonant Pavement Breaker (RPB) equipment used on SR-36 produced fractured particle size distribution and steel debonding required by ODOT specifications.</p> <p>The principal recommendation of the study is to improve ODOT's specifications for fractured slab techniques. On all types of fracturing projects, the quality control requirements need to be modified to require that test pits be more frequently used to ensure that the specified particle size distributions are in fact being achieved throughout the depth of the slab. On rubblize projects, the present particle size distribution requirements need to be re-examined to ensure that the fracturing operation will avoid, not merely delay, reflection cracking in the subsequent overlay.</p>					
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**INVESTIGATION OF PAVEMENT CRACKING ON SR-4 AND  
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**1. PROBLEM STATEMENT**

**1.1 Need for Follow-up Evaluation of the SR-4 Project**

In 1993, the Ohio Department of Transportation (ODOT) constructed test sections on State Route 4 (SR-4) to study the effectiveness of Breaking and Seating (B/S) as a rehabilitation strategy for retarding reflection cracking in asphalt overlays of jointed reinforced concrete pavements (JRCP). After being in service for nine years, the break and seat test sections displayed relatively few reflection cracks. In 2004, however, a significant number of transverse cracks were observed to have occurred directly over the underlying joints in the concrete layer. To determine the implications of this recent cracking on the expected performance and maintenance requirements of future break and seat projects, an in-depth forensic analysis of the nature and mechanism of the cracking is needed.

**1.2 Need for Comparative Assessment of Alternative Pavement Breaking Equipment**

The pavement breaking operation on the SR-4 project was performed with a pile hammer. Several other types of pavement breakers are now available, including the Multi-Head Breaker (MHB) and Resonant Pavement Breaker (RPB). Performance claims for this competitive equipment include increased production rates (hence, potentially lower construction costs) and the ability to produce a variety of controlled

breaking patterns (hence, permitting pre-overlay fracturing techniques to potentially be used on a greater number of candidate distressed concrete pavements, with differing subgrade conditions, etc). To permit ODOT to evaluate the merits of these performance claims - and thus to provide for more informed, cost-effective decisions regarding the type(s) of equipment permitted to be used on future concrete pavement rehabilitation projects, the evaluation of the SR-4 project needs to be expanded to include a comparable assessment of projects constructed with the MHB and RPB equipment.

## **2. OBJECTIVES AND SCOPE OF THE EVALUATION**

This evaluation has three basic objectives:

- To determine the cause of the recent cracking on the SR-4 project, and the implications on the performance of future break and seat projects.
- To determine the extent to which the pile hammer, MHB, and RPB equipment consistently produce the pavement breaking patterns and fractured particle sizes required by ODOT specifications.
- To compare the features of the three types of breaking with respect to other factors bearing on the issue of cost-effectiveness (e.g., achievable production rates, unit construction cost, particle shape, etc).

To accomplish these objectives, a program of field evaluations was undertaken on the SR-4 project and three other test projects. On two of the latter projects, the MHB equipment was used to break the pavement; on the third project, the RPB equipment was used.

At each site, a test pit was dug and a visual assessment of the condition of the fractured pavement, the overlay and subbase/subgrade was made. Measurements were made of the fracturing pattern at the surface of the concrete and gradation tests were performed to determine the particle size distribution at various depths within the fractured slab. On the MHB and RPB projects, deflection tests were performed to determine the effect of the observed breaking patterns on the stiffness of the pavement layers.

To complement the field observations made on ODOT projects, the researchers met with staff of the Arkansas DOT to discuss their experience with the MHB and RPB equipment gained as part of a monumental (\$1.3 billion, 360 centerline mile) five-year concrete pavement rehabilitation program now nearing completion in that state. Following this, the researchers attended a Rubblization demonstration project organized by the Alabama DOT that described the State's experience with MHB and RPB equipment and resulting pavement performance issues.

This report synthesizes all the activities performed in this study, including a review of ODOT's experience with fractured slab techniques, analysis of data from field investigations, lessons learned from other DOTs and discusses and presents specific guidelines to ODOT for future consideration of fractured slab techniques in Ohio.

### **3. BACKGROUND AND SIGNIFICANCE OF THE WORK**

#### **3.1 Nature and Significance of the Reflection Cracking Problem**

Since the time when highway agencies first began using asphalt overlays as a means of rehabilitating deteriorated concrete pavements, engineers have sought an effective means for preventing reflection cracks in the finished overlay. These reflection

cracks – which begin as a pattern of narrow, difficult-to-seal cracks that mirror the joints and cracks in the underlying concrete pavement – permit water to enter the pavement, triggering a process of progressive deterioration that commonly is the eventual cause of failure in the overlay.

Reflection cracks are primarily caused by tensile stresses in the asphalt layer which are induced by the expansion and contraction of the Portland Cement Concrete (PCC) pavement in response to temperature changes. Reflection cracking can also result from shear stresses created by differential deflection between the approach and leave slabs. In either case, when the stress exceeds the strength of the asphalt overlay, a crack begins and eventually propagates to the surface.

### **3.2 Proposed Solutions**

Over the years, a wide variety of generic treatments and proprietary products have been proposed to eliminate, delay, or lessen the severity of the reflection cracking problem. These include the use of bond breakers (e.g., sand layers, plastic sheeting, metal strips), reinforcement in the overlay, stress-absorbing membranes and interlayers, waterproofing treatments, stronger and thicker overlays, and saw-and-seal procedures. Some of these earlier proposed solutions were definitely failures, while others yielded mixed success and/or inconclusive results.

For twenty years or more, an increasing number of state DOTs have routinely or experimentally used a family of “fractured slab techniques” to provide a cost-effective solution to the reflection cracking problem. The fractured slab techniques include Crack and Seat (C/S), Break and Seat (B/S) and, Rubblize and Roll(R/R). Each of these procedures shares a common premise: fracturing concrete pavement prior to overlay will

reduce the slab action and thereby minimize thermal movements to such an extent that reflection cracking of the overlay is prevented, delayed, or reduced in severity and extent.

For non-reinforced plain jointed concrete pavements, “cracking and seating” may be sufficient to decrease the effective slab size of the concrete so as to reduce the opportunity for reflection cracking. For reinforced concrete pavements, cracking is often not sufficient; the amount of fracturing energy applied to the pavement must be sufficient to “break” both the bond to the steel and the concrete. As the name implies, the “rubblizing” alternative carries the fracturing process to the extreme: complete destruction of the concrete slab and all concrete slab action. The rubblizing process effectively reduces the existing slab to an in-place crushed aggregate base. Since the existing pavement distresses and joints are obliterated, rubblizing is reported to be the most effective of the fractured slab techniques in preventing reflection cracking.

The three fracturing techniques are distinguished primarily on the basis of the specified range of sizes of the fractured particles. The size ranges traditionally required in Ohio [1, 2, 3] are shown in Table 1.

**Table 1. Fractured Pavement Particle Sizes Required by ODOT**

Fracturing Technique	Particle Size	
	Predominant/Target	Maximum
Crack and Seat	4' x 4'	5'
Break and Seat	18"	30"
Rubblize and Roll	1-2"	2" (above reinforcing steel) 6" (below reinforcing steel)

For the pavement designer, determining the appropriate fracturing technique and/or particle size for a particular distressed concrete pavement involves striking an economical balance between two performance extremes:

- No fracturing or insufficient fracturing of a concrete pavement prior to overlay will provide a strong base for paving, thereby requiring a relatively thin overlay, but one which on account of its stiffness--is highly susceptible to reflection cracking and consequent reduced service life.
- Excessive fracturing will drastically reduce the stiffness of the concrete, which eliminates the potential for reflection cracking, but which provides a weaker base for paving, requiring a thicker overlay to compensate for the loss of support.

### **3.3 ODOT's Use of Fractured Slab Techniques**

#### **3.3.1 *Past Experience***

Since 1984, ODOT has been a leader in the systematic use and evaluation of fractured slab techniques. The focus of this continuing initiative is on developing a cost-effective alternative to the Ohio's conventional Repair and Overlay (R/O) procedure for the rehabilitation of existing concrete and composite pavements that will retard or eliminate the recurring problem of reflection cracking in composite pavements.

As in other states, Ohio's use of pre-overlay fracturing began with C/S and expanded over time to include B/S and R/R. Between 1984 and 1992, ODOT rehabilitated a total of 205 centerline miles of concrete pavement using C/S and B/S procedures [4, 5]. The earliest of these projects used a pile hammer to accomplish the breaking; later, use of the guillotine hammer predominated, due to the higher achievable

production rates for that equipment (typically, five vs. one lane-mile of fractured pavement per day).

In 1988, ODOT participated in the Federal Highway Administration (FHWA) research project, “Break and Seat of Jointed Concrete Pavement (SP-202)”. This nationwide study was undertaken to investigate the effect of various degrees of pre-overlay fracturing of JRCP on the subsequent overlay performance. In Ohio, four test sections were constructed on I-70 in Muskingum County: a control section, a 6” (15 cm) break pattern, an 18” (45 cm) break pattern, and a 30” (76 cm) break pattern. Each section was a minimum of 1,000’ (305 m) long and pavement fracturing was accomplished using a guillotine hammer [6]. Over the first few years of service, each of these B/S test sections performed about the same and provided only a modest reduction in the amount of reflection cracking compared to the control section.

During a 1992 review of Ohio’s pavement rehabilitation program by the Ohio Division of the FHWA, it was noted that (a) ongoing performance studies of the effectiveness of B/S on JRCP were inconclusive and (b) inconsistent project-to-project breaking patterns and performance were apparently being produced by the guillotine hammer [5]. As a result, the FHWA recommended that ODOT restrict the use of the B/S technique to non-reinforced concrete pavements. In response, ODOT imposed a moratorium on breaking and seating of JRCP and initiated a research project in association with the University of Cincinnati (UC) to validate the FHWA findings. The goal of the study was to systematically evaluate the effectiveness of breaking and seating jointed reinforced concrete pavements prior to asphalt overlay.

The ODOT/UC study was conducted in two phases between 1992 and 2003. In the first phase, two test projects were constructed and monitored over a 2 ½ year period. In the second phase, performance monitoring of the test sections was extended to establish the long-term effectiveness of the B/S techniques on JRCP [7].

As part of ODOT/UC study, nine test sections were constructed by milling the original AC layer, breaking and seating the concrete slabs and constructing new AC overlays. Control sections were constructed adjacent to the B/S sections in the same way, but without breaking the underlying concrete slabs. Each of these sections was one mile long (1.6 km). Four sections were on I-71 in Fayette and Madison Counties. The remaining five sections were on SR-4 in Green and Montgomery Counties. The primary variables included in the study were: type of pavement breaker (pile hammer and guillotine hammer), traffic (high and medium truck traffic), and the type of soil (A-4 and A-6).

By 2002, it was apparent that the B/S sections had out-performed the control sections, particularly on the SR-4 project where a pile hammer was used. On the SR-4 project, the two B/S sections displayed 7% and 17% joint reflection cracks, as compared to 80% and 100% for the companion control sections. On the I-71 project, a B/S section constructed using a guillotine hammer displayed 42% joint reflection cracks, compared to 100% for the untreated control. The better performance provided by the pile hammer relative to the guillotine hammer is attributed to the ability of the pile hammer to provide through cracking of the slab in *all* directions, whereas the fracturing energy transmitted by the guillotine hammer is focused in a single direction.

Based on the study results, the UC researchers concluded that “*breaking and seating is an effective technique for the rehabilitation of composite pavements and it provides a cost-effective solution for the maintenance and rehabilitation of in-service composite pavements*”.

### **3.3.2 Future Plans**

The results of the present study are expected to support two ongoing pavement rehabilitation initiatives by ODOT’s Office of Pavement Engineering (OPE):

#### **3.3.2.1 White Paper on Recommended Use of B/S in Ohio**

In response to UC study findings, OPE is currently developing a white paper entitled “Recommendations for the Use of Break and Seat in Ohio” [4]. This policy document will describe the history of fractured slab techniques in Ohio, critically review and summarize relevant research studies, compare the cost of using fractured slab techniques to the conventional repair and overlay procedure, and provide specific recommendations for the future use of the B/S procedure in Ohio.

#### **3.3.2.2 Increasing use of Rubblization Projects in Ohio**

Based on the continuing reports of successful use of the R/R technique by other states and potential for significant long-term cost savings [8], ODOT has begun to focus on R/R as an alternate procedure to B/S to eliminate reflection cracking. Beginning in 1995, ODOT has constructed some 11 R/R projects.

As noted in Section 3.2, use of pre-overlay fracturing in a pavement design in a balancing act: a smaller particle size reduces the likelihood of reflection cracking (thus increasing service life), but will provide weaker support, necessitating a thicker overlay.

In Ohio, the construction cost of a pavement rehabilitated with a conventional rubblization process (i.e., one in which the concrete is reduced to relatively small fragments) is significantly higher than one rehabilitated with break and seat. In the first place, the required overlay thickness on an Ohio rubblized pavement is much higher than that on a B/S pavement (structural coefficient for B/S is 0.27 and 0.14 for R/R). Added to this is the greater incremental cost of the fracturing process: the cost of rubblization is typically about 3 to 4 times that of breaking and seating (i.e., \$2-3 vs. \$0.5-0.7 per square yard).

However, based on literature reports [9, 10, 11] of success with so-called “Coarse Rubblization”, it seems possible to determine an *optimum* maximum particle size-larger than the conventional maximum for rubblization, but smaller than that for B/S-which would reduce the required thickness of the overlay, while still minimizing the potential for reflection cracking. If so, this could provide a breakthrough in providing a cost-effective solution to Ohio’s reflection cracking problem.

The suppliers of the MHB and RPB machines each claim that their equipment is capable of consistently providing the controlled breaking patterns that are essential to the success of coarse rubblization. While the focus of the equipment evaluations in the present study is on the ability of particular equipment to produce the desired fractured patterns and particle sizes for B/S, some field experimentation was performed to provide insight on the equipment’s capability to eventually provide the optimum breaking pattern sought in coarse rubblization.

### ***3.3.3 Equipment for Fracturing Pavements***

#### **3.3.3.1 Pile Hammer**

Pile hammers were used in some of the earliest C/S and B/S projects (Figure 1). The impact energy of the driver is determined by the amount of fuel that goes to the hammer; the hammer rate typically remains constant at about 50 blows per minute [12]. The breaking pattern is controlled by the speed of the tractor unit. Multiple passes of the hammer are required to achieve full lane-width fracturing.



**Figure 1. Pile Hammer**

### 3.3.3.2 Multi-Head Breaker

The Badger Multi-Head Breaker came into use in 1997. This equipment uses a series of independently-controlled, high-amplitude drop hammers to fracture the slab (Figure 2).



**Figure 2. Multi-Head Breaker**

Typically, there are between 12 and 16 hammers, mounted in pairs in two rows (“heads”). The hammers in the rear row are offset from those in the forward row to provide continuous breakage from side to side. Each of the 8-inch wide hammers weighs between 450 – 680 kg (1000 – 1500 lbs). Hammers can be dropped from variable heights (1 to 5 feet) and cycle at a rate of 30 to 35 impacts per minute [13].

In comparison to other breaking equipment, the MHB unit reportedly has two main advantages. First, the MHB can fracture a full lane width in a single pass at high production rates (up to 1.5 miles per day on rubblized projects). This one-lane/one-pass operation not only can lead to reductions in the unit cost of the fracturing operation, but also helps avoid costly road closures and crossovers, and the associated disruptions of traffic. Secondly, the amount of fracturing energy transferred to the pavement during each impact can be adjusted within wide limits (2,000 to 12,000 foot-pounds) through adjustment of the drop height. This permits the operator to control the size of the fractured particles

### **3.3.3.3 Resonant Pavement Breaker**

The Resonant Pavement Breaker-also known as the Vibratory or Sonic Pavement Breaker-reportedly is the most widely-used type of equipment on rubblization projects, having been used on about 75% of all rubblization projects let since the process was developed in 1986 [14]. Several models of this equipment are available, varying in size and weight. The PB-4 model is widely used on highway projects (Figure 3).

In this machine, a resonance is set up in a beam by a rotating eccentric weight. A shoe attached to the end of the beam rides along the pavement surface, striking the pavement with low amplitude (1/2 to 1 inch), high frequency impacts at the resonant

frequency of the slab (about 44 Hz), causing the concrete to break apart. The vibrating shoe fractures the pavement in strips as the machine moves along the unfractured edge of the pavement. This vibrating beam has been described as a giant tuning fork [15, 16]. Production rates are reportedly similar to the MHB, and depend on the strength and thickness of the slab and underlying subbase/subgrade.



**Figure 3. Resonant Pavement Breaker**

Performance claims made for the RPB equipment include:

- Complete debonding of the reinforced steel, which is a prerequisite to avoiding subsequent reflection cracking;
- An angular fracturing pattern that provides greater support (i.e., higher effective modulus) and thus permits thinner overlays to be used; and
- No damage to the base material-hence, better load distribution-because the energy from the low amplitude impacts is dissipated within the slab [14].

Pavement fracturing operations can be conducted while maintaining traffic in adjoining lanes. However, because the RPB equipment can encroach on the adjoining lane at some stages of its multiple-pass operation, more extensive traffic controls may be required than with the MHB equipment. Also, because one side of the 30-ton RPB machine travels on rubblized concrete during the fracturing operation, there is a potential for deformation of the underlying base course or subgrade in, e.g., areas of weak soil support or a high water table [17].

## 4. RESULTS AND ANALYSIS

### 4.1 Pavement Cracking on the SR-4 Project

#### 4.1.1 Project Location and Construction Details

The SR-4 project is a 4-lane divided facility located near Dayton in Greene and Montgomery County (Figure 4). The existing 9” thick concrete pavement was constructed using ODOT’s standard contraction joint design (1/2” sawed joints at 60’). The original construction included reinforcing steel and dowels.

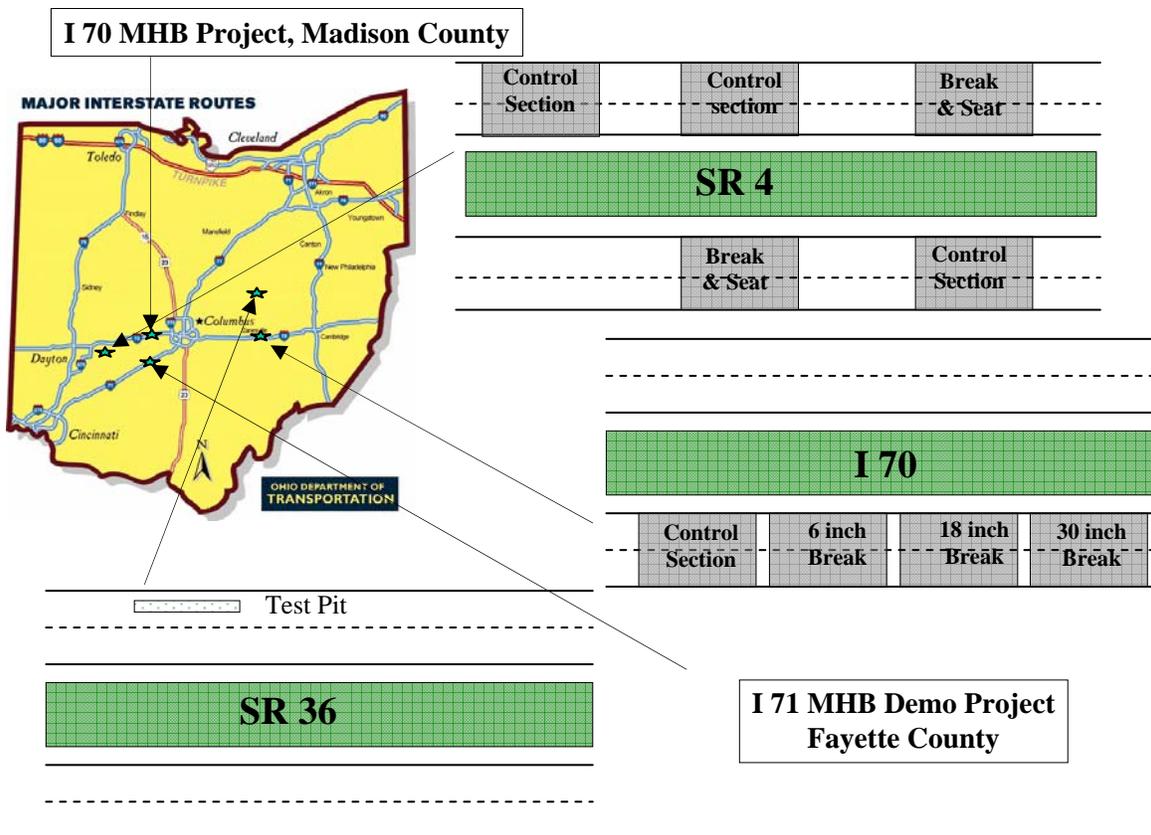


Figure 4. Location and Layout of Test Sections

In 1993, five test sections were constructed to study the effectiveness of breaking and seating before constructing Asphalt Concrete (AC) overlay. Two sections were constructed by milling the original AC, followed by breaking and seating the concrete

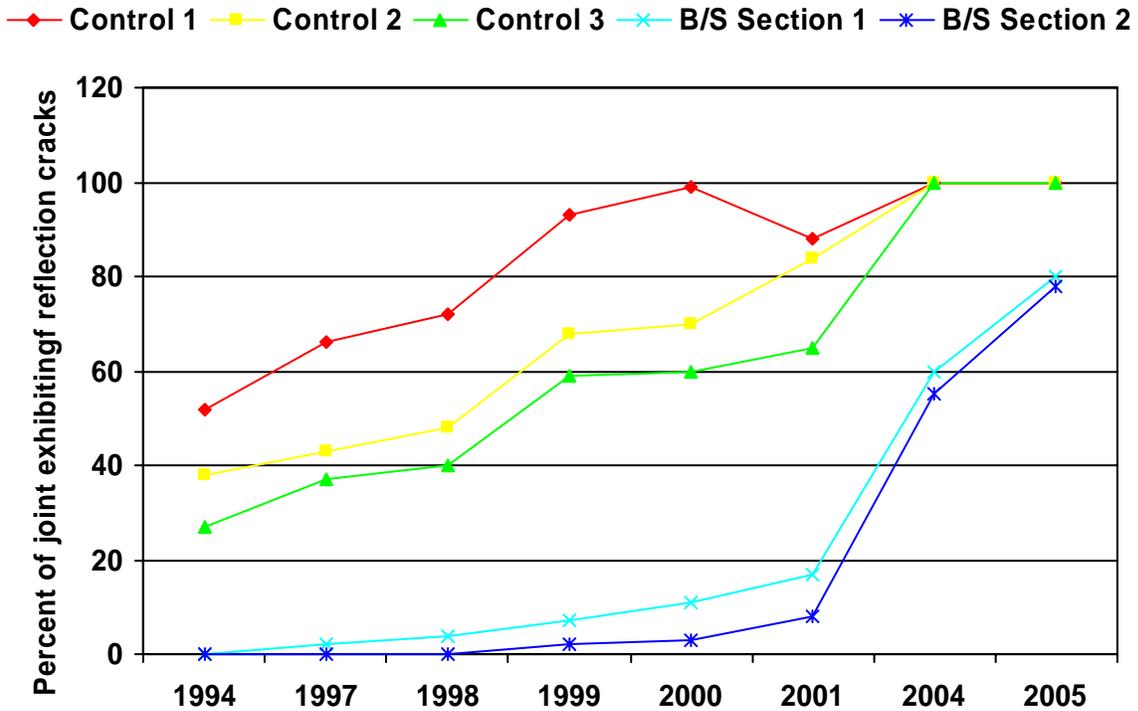
slabs before constructing new AC layers. Three control sections were constructed in the same way, but without breaking the underlying concrete slabs. The concrete pavement underlying each of the test and control sections contained a total of about 90 transverse joints.

#### **4.1.2 *Historical Performance and Current Condition***

As shown in Figure 5, throughout the service history of the SR-4 project, the overlay on the break and seat test sections displayed far less reflection cracking than the overlay on the untreated control sections. By 2001, the level of cracking and related distress on those control sections had reached the point that District staff concluded that rehabilitation by milling and overlay was needed. In contrast, at that time, it was noted that no such rehabilitation was needed on the B/S test sections.

In February 2004, an inspection indicated that the level of cracking on the B/S test sections had suddenly increased to the point where about 50% of the joints were affected. By October 2005, a further increase to about 78% joint cracking was noted. Since all the latest cracking occurred at or near joints in the underlying concrete pavement, it appears to be classical reflection cracking, rather than fatigue cracking.

Thus, after 10+ years of service, it seems that the slab action has been restored in the underlying concrete due to (a) insufficient fracturing and/or steel debonding during construction or (b) closure of the initial fractures by some in-service slab-stiffening mechanism.



**Figure 5. Progression of Reflection Cracking on SR-4**

Photos of typical joint reflection cracks in the test and control sections in late 2005 are presented in Figures 6 and 7. As shown, the cracking on the B/S sections is generally less pronounced than on the companion control sites, and consists mostly of single-line cracks. In contrast, the reflection cracking and related distress on the control sites is significantly more severe. Many of the cracks are in the final stages of a well-known pattern: single-line cracks that have progressed to double-line cracks, with spalling of the pavement material between the two cracks.



Break and Seat Sections



Control Sections

**Figure 6. Appearance of SR-4, Station 105-160, October 2005**



Break and Seat Sections

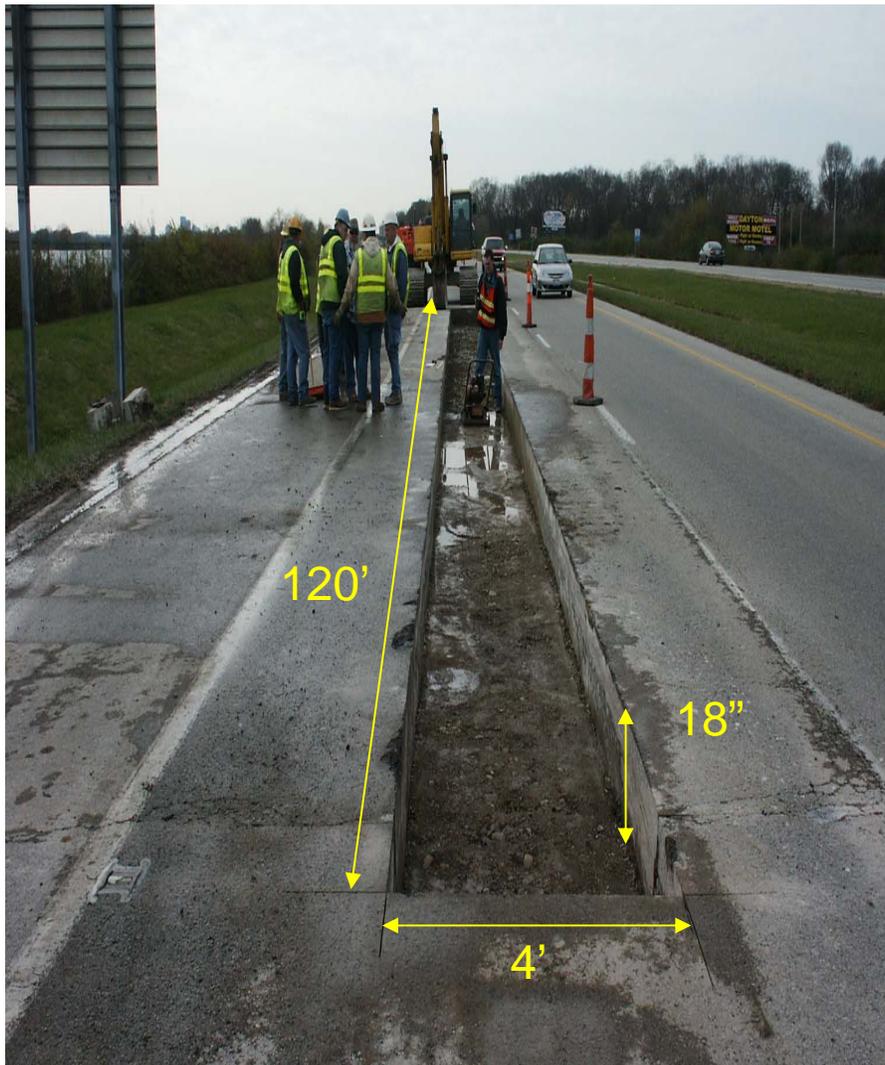


Control Sections

**Figure 7. Appearance of SR-4, Station 217-270, October 2005**

### 4.1.3 Evaluation Methodology

To permit a detailed examination of the condition of the fractured concrete, a large test pit was constructed in the center of the outside lane on one of the B/S test sections (Figure 8). The substantial length of the pit (120 feet) ensured that a representative sample was obtained for the condition evaluation.



**Figure 8. Test Pit on SR-4, Montgomery County, Mile 22.7-22.8**

The sequence of operation for constructing the pit involved layout, saw-cutting, and pavement removal using a backhoe. Several large, square-cut samples were removed intact for detailed inspection (Figure 9). After the sides of the pit were cleaned by water washing, the pavement around the entire perimeter of the pit was examined to assess the nature and extent of pavement fracturing and reinforcing steel debonding.



**Figure 9. Sample Collected for Detailed Inspection**

The subbase layer was examined and tested for its support values using a Dynamic Cone Penetrometer (DCP). This 6” layer was then removed to expose the subgrade for similar testing (Figure 10).



**Figure 10. Subgrade Exposed for DCP Test**

#### ***4.1.4 Results of Visual Examination***

##### **4.1.4.1 Fracturing Patterns and Particle Sizes**

When the break and seat operation was conducted in 1993, compliance with specification requirements for fractured particles was based strictly on observations of the finished surface; no test pits were dug to determine the particle sizes being produced throughout the depth of the slab. Those visual observations indicated that the pile hammer was indeed producing the desired results.

Examination of the test pit confirms that, in the case of quality control of pavement fracturing operation, the aphorism, “appearances can be deceiving”, is certainly true. In the first place, a number of long, 5-6 feet sections of the exposed slab displayed

no signs of fracturing whatsoever (Figure 11, 12). As noted earlier, according to the project specifications, the maximum permissible particle size was 30” and the target size was 18”. Further, in many cases, the cracking produced was not near-vertical *through* cracking of the slab that was expected and desired, but rather consisted of mostly horizontal, shallow fracture planes (Figures 12-15).



**Figure 11. Exposed Slab Showing No Fracture**



**Figure 12. Horizontal, Shallow Fractured Plane**



**Figure 13. Horizontal, Shallow Fractured Plane**



**Figure 14. Horizontal, Shallow Fractured Plane**



**Figure 15. Horizontal, Shallow Fractured Plane**

#### 4.1.4.2 Steel Debonding

In those sections of the concrete slab where the reinforcing steel was exposed and could be examined, it was apparent that the pile hammer had generally not succeeded in breaking the bond between the steel and concrete (Figure 16).



**Figure 16. Condition of Reinforcing Steel**

#### 4.1.4.3 Soil Support/Penetration Tests

When rehabilitation was performed in 1993, subgrade soil samples were collected and tested in the laboratory primarily to establish the soil type. During the present investigation, DCP tests were conducted at three locations in the test pit to collect additional information about the in-situ subgrade soil properties. This test data was not used in the current investigation; however, the results may be significant to the District engineers for future maintenance and rehabilitation. The results are presented in Appendix I.

## **4.2 Multi-Head Breaker Demonstration**

### **4.2.1 Test Projects**

The capabilities of the MHB were evaluated on two test projects: a section of I-70 in Madison County and on I-71 in Fayette County (Figure 4). The I-71 project contained the most experimental variables (break and seat as well as rubblized fracturing patterns) and the evaluation methodology included deflection tests, as well as the visual examination and gradation tests. The I-70 test project included only visual examination and gradation tests.

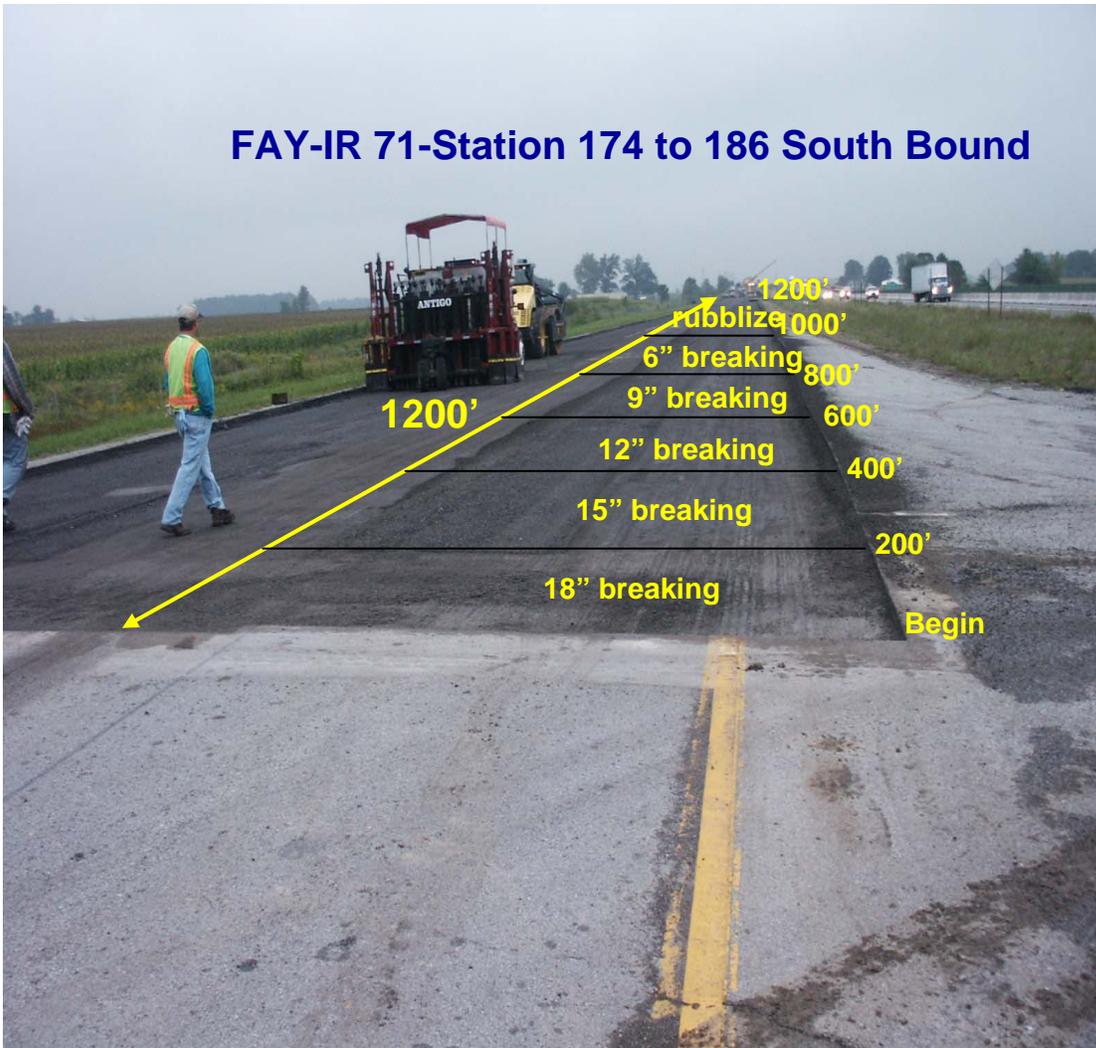
The existing 9-inch thick concrete pavement on I-71 was constructed in 1964 using ODOT's standard contraction joint design. A 6" thick bituminous overlay was constructed in 1980. In July 2005, the existing concrete pavement was being removed in preparation for a reconstruction using a full-depth asphalt pavement.

The Continuously Reinforced Concrete Pavement (CRCP) on I-70 was constructed in 1968. In July 2005, the existing bare concrete was being removed in preparation for an initial asphalt overlay.

### **4.2.2 Test Layout and Procedures**

On the I-71 project, the MHB equipment was used to demolish the concrete pavement and demonstrate the capabilities of MHB to produce various fracturing patterns.

As shown in Figure 17, for each of the first five sections, the contractor was asked to produce a fracture pattern with a nominal target particle size of 18, 15, 12, 9 and 6 inches, respectively; the last section was to be rubblized in conformance with ODOT specifications.



**Figure 17. MHB Demo Section, FAY 71-Station 174 to 186, Southbound Lane**

After milling the existing overlay, the pavement fracturing operation proceeded as planned. The President of the contracting firm was present on-site to guide the operation.

On the I-70 project, the observations were made on a randomly selected day's production during the ongoing rubblization operation. The work was performed with the same type of equipment as on I-71, but by a different contractor.

On both projects, to provide for a subsurface examination of the fractured concrete and full-depth gradation sampling, a full-lane width test pit was dug with a backhoe in each test section (Figure 18). A grab sample of the fractured concrete above the reinforcing steel was obtained by shoveling prior to the excavation. The sizes of the particles below the reinforcing steel was physically measured using a measuring tape.



**Figure 18. Making Test Pit to Study Pattern of Breaking**

To determine the effect of various fracturing patterns on the structural behavior of I-71 pavement layers, deflection measurements were made with a Falling Weight Deflectometer (FWD) before fracturing and after fracturing and rolling with a vibratory

roller (Figure 19). In each test section, a series of eight before and after measurements were made with the FWD.



**Figure 19. Rolling with a Vibratory Roller**

#### **4.2.3 Results of Visual Observations**

The appearance of the fractured pavement surface on each of the I-71 test sections is shown in Figures 20-25; the rubblized surface on I-70 is shown in Figure 26. As shown in these photos, on both projects, the surface appearance suggested that the desired particle sizes were indeed being obtained, with only a minimum of oversized material. However, once the test pits were opened, it was immediately obvious that on the I-71 project, a significant amount of large, un-cracked pieces were being produced (Figures

27-32). This was generally not the case on the I-70 project; there, the initial visual inspection of the excavated concrete revealed relatively few overly large pieces (Figures 33, 34).



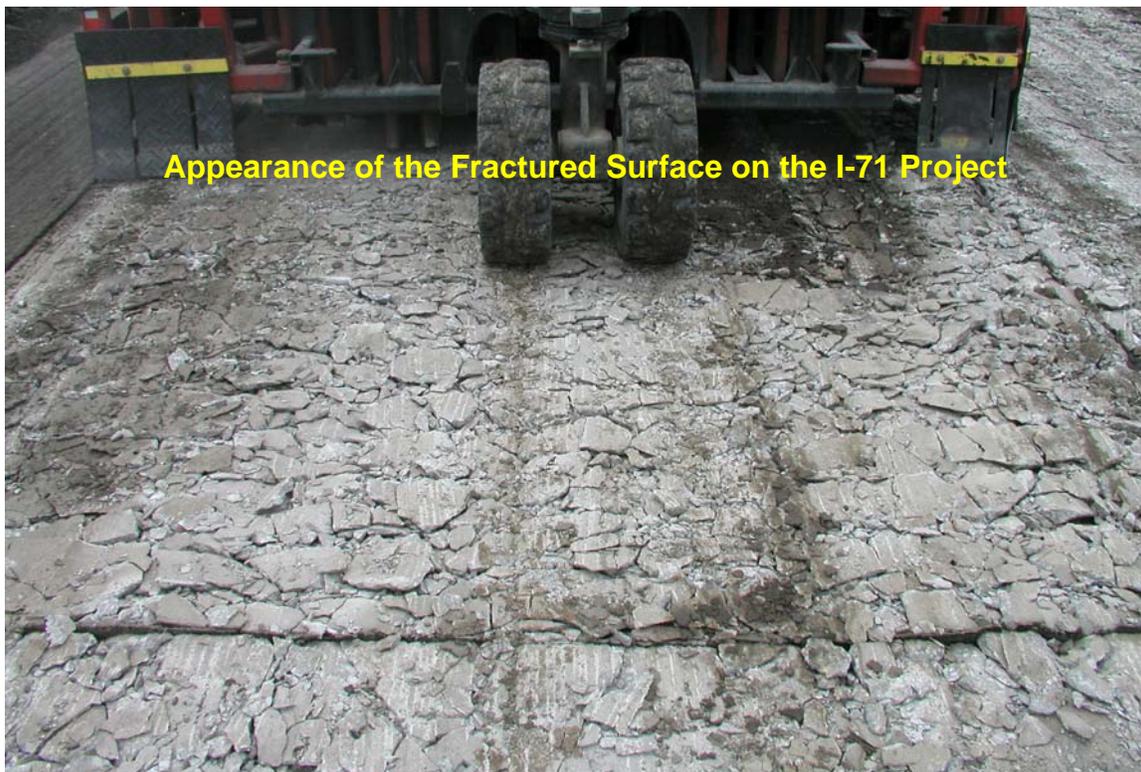
**Figure 20. 18" Breaking Pattern**



**Figure 21. 15” Breaking Pattern**



**Figure 22. 12” Breaking Pattern**



**Figure 23. 9” Breaking Pattern**



**Figure 24. 6” Breaking Pattern**



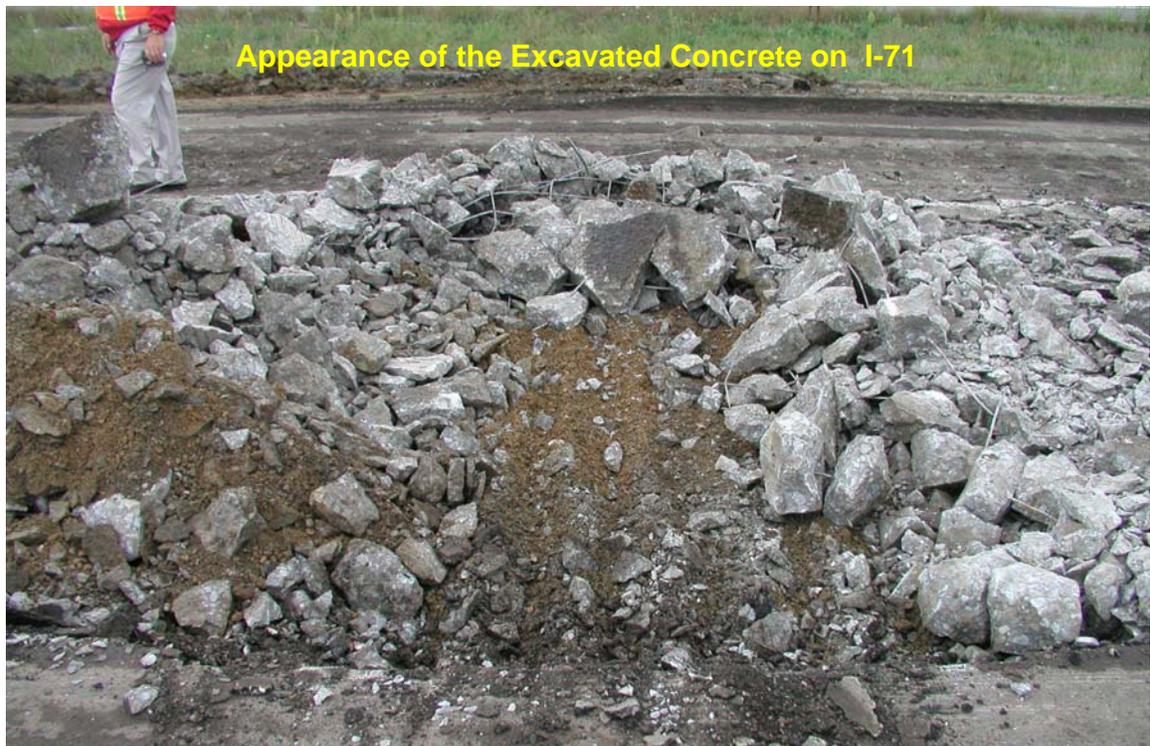
**Figure 25. Rubblize Pattern**



**Figure 26. Appearance of Fractured Surface on I-70 Project**



**Figure 27. 18” Breaking Pattern**



**Figure 28. 15” Breaking Pattern**



**Figure 29. 12” Breaking Pattern**



**Figure 30. 9” Breaking Pattern**



**Figure 31. 6” Breaking Pattern**



**Figure 32. Rubblize Breaking Pattern**



**Figure 33. Appearance of Excavated Concrete on I-70 Project**



**Figure 34. Appearance of Excavated Concrete on I-70 Project**

As it turned out, precisely determining the extent to which the reinforcing steel was debonded by the fracturing operation based on visual inspections of excavated concrete was a delicate task. In general, it appeared that on the I-71 project, the MHB achieved only mixed success in debonding. On the other hand, the rubbleizing operation on I-70 appeared to have consistently debonded the steel (Figure 35).



**Figure 35. Steel Debonding on I-70 Project**

#### 4.2.4 Gradation Test Results

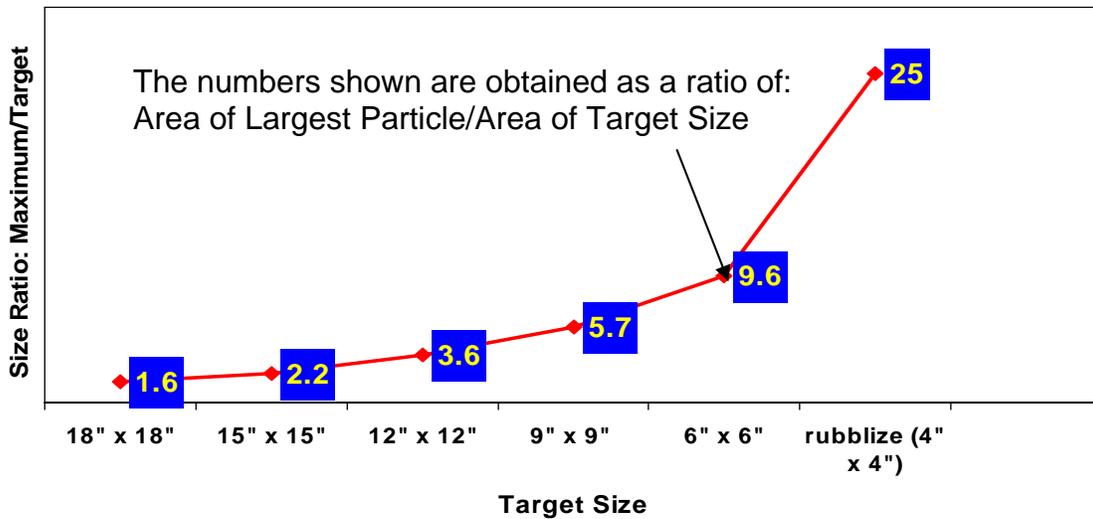
To provide a more specific indication of the distribution of fractured particle sizes produced by the MHB operation on the I-71 project, measurements of the test pit material dimensions were made and organized by size *categories*: the maximum, minimum, and typical fragment size within a particular test section (Table 2).

**Table 2. Size of Concrete Fragments on the I-71 Project**

Desired maximum size	Above reinforcing steel			Below reinforcing steel		
	Maximum	Minimum	Typical	Maximum	Minimum	Typical
18" x 18"	11" x 17"	¼"	6" x 8"	22" x 24"	5" x 6"	12" x 16"
15" x 15"	11" x 17"	¼"	6" x 8"	22" x 22"	4" x 5"	12" x 14"
12" x 12"	9" x 14"	¼"	5" x 6"	20" x 26"	4" x 5"	10" x 12"
9" x 9"	7" x 11"	¼"	4" x 5"	20" x 23"	4" x 5"	9" x 12"
6" x 6"	6" x 9"	¼"	3" x 3"	15" x 22"	4" x 5"	9" x 12"
Rubblize	6" x 9"	¼"	2" x 2"	20" x 20"	4" x 4"	9" x 12"

As shown in Table 2, for each of the six test sections, the portion of the slab above the reinforcing steel was broken into fragments which were typically no larger than the desired target size. Below the steel, however, most of the fragments were significantly larger than the target size. Throughout the project, the maximum particle size was in a narrow range of about 20" x 20" to 22" x 24". Similarly, the size of a "typical" fractured particle in the portion of the slab below the steel varied very little from one test section to the next, commonly being about 9" x 12".

The disparity between the target size and observed maximum size of fractured particles below the reinforcement on I-71 is shown graphically in Figure 36.



**Figure 36. Size Ratio of I-71 Slab Fragments**

A similar gradation test was performed on I-70 project. There, about 2% of the fragments from the portion of the slab above the steel were a nominal 6" size, about 20 percent were on the order of 4", and the remainders were smaller. Below the reinforcing steel, about 40-60% of the fragments were 4 to 6" in size and about 20% ranged from 6-9" in their largest dimension.

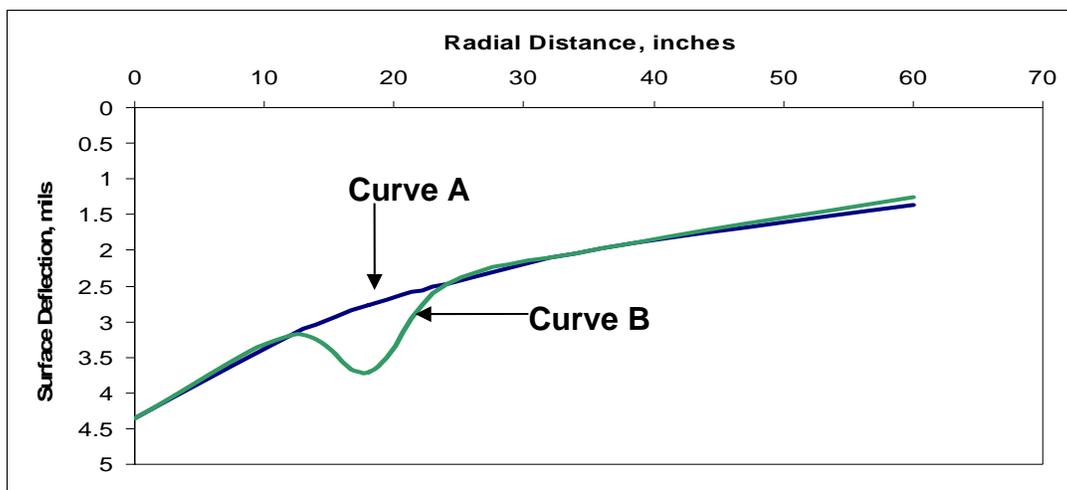
As noted earlier, ODOT's current rubblization specification requires that (a) the portion of the slab above the reinforcing steel is to be reduced to 1-2" in size and (b) no particle is to exceed 6" in its maximum dimension. As outlined above, the fracturing pattern produced by the MHB equipment failed to comply with those requirements on either the I-71 rubblization section or the I-70 work.

#### **4.2.5 Deflection Test Results**

The primary intent of collecting deflection data was to backcalculate the modulus (stiffness) of the fractured PCC layer and to investigate a possible variation due to

different breaking pattern. While the modulus of intact concrete slabs can generally range from 3,000,000 to 6,000,000 psi (depending on their condition), it is logical to expect a reduction in this value for the fractured layers due to a reduction of the flexural strength and an increase of surface deflection and subgrade stress.

The FWD deflection data collected on the I-71 project was analyzed using *EVERCALC 5.0*, a backcalculation program developed by the Washington State Department of Transportation [17]. This program, designed to backcalculate the modulus of pavement layers, works on the premise that the deflection is maximum under the center of wheel load and gradually decreases along the radial distance. A typical deflection basin measured using FWD is shown as *Curve A* in Figure 37.

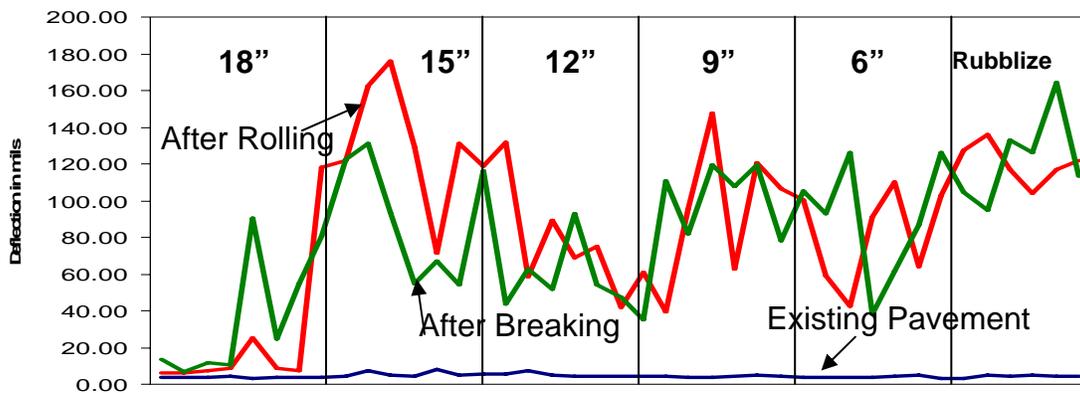


**Figure 37. Typical Deflection Basins**

When deflection measurements are made on finished pavement surface, deflection basins depicting a shape illustrated as *Curve A* is generally obtained. However, when deflection studies were conducted directly on fractured concrete layer after rolling (as on the I-71 project), but without the placement of AC overlays, often one or more deflection values at certain distances were higher than the adjacent values (an example is shown as

Curve B). While analyzing such deflection basins, the *EVERCALC* program terminated without producing any results. The irregular pattern of deflection basins is due to the discontinuities introduced in the fractured layer. As a result, the deflection data could not be used to either backcalculate the modulus values or to calculate any parameter that would consider the shape of deflection basin. Hence, the analysis deflection data was limited to comparing the maximum deflection values.

Figure 38 shows the variation in maximum deflection value along the I-71 project on the existing pavement, on the fractured layer after breaking and after rolling for each breaking pattern. As it can be seen, the deflection value of the existing pavement was very consistent along the project indicating a structurally homogeneous section. As expected, the deflection values increased significantly after breaking. However, there is no definite relationship between the observed maximum deflection and the target fractured particle size. A similar observation can be made using the deflection values after rolling. Thus it is concluded that, the deflection values increased due to breaking but the variation in maximum surface deflection values did not significantly change due to the breaking pattern.



**Figure 38. Variation in Maximum Deflection on the I-71 Project**

### **4.3 Resonant Pavement Breaker Evaluation**

#### **4.3.1 Project Location and Construction Details**

To-date, fourteen R/R projects have been constructed by ODOT. On ten of these, the fracturing operation was performed using the RPB; on four, the MHB was used.

One of these RPB projects—a section of SR-36 in Coshocton County (Figure 4)—was selected for detailed evaluation in this study. The existing 9-inch thick concrete pavement on COS-36 was constructed in 1964 using ODOT’s standard contraction joint design. In 1992, the concrete was rubblized and overlaid with 9” of bituminous concrete.

#### **4.3.2 Historical Performance and Current Condition**

After 13 years of service, the rehabilitated COS-36 pavement has remained in generally good condition. The asphalt surface shows some raveling and slight longitudinal cracking resulting from a cold joint, with occasional reflection cracking (Figure 39).



**Figure 39. General Condition of COS-36 Pavement**

#### **4.3.3 Evaluation Methodology**

The fracturing pattern produced by the RPB on the COS-36 project was evaluated on the basis of a visual examination of test pit material. As on the SR-4 project, a large (120' x 4' x 18" deep) saw-cut was used to ensure a representative sample (Figures 40, 41).



**Figure 40. Layout of Test Pit on COS-36**



**Figure 41. Saw-cutting Test Pit on COS-36**

The effect of the fracturing on the resultant stiffness of the pavement layers was determined from a series of FWD deflection measurements. These deflection tests were performed at locations corresponding to the pre-existing doweled joints and at locations between consecutive joints.

#### **4.3.4 Results of Visual Examination**

##### **4.3.4.1 Particle Sizes**

Figures 42 and 43 are photos illustrating the size distribution of the fractured particles in the test pit. As shown in Figure 42, the pieces near the surface appeared to consistently be in the 1-2” range required by ODOT specifications. Similarly, throughout the depth of the slab, all of the fractured pieces appeared to be smaller than the 6” maximum size permitted by the rubblized specification, with about 90% being in the range of 2-4” in size (Figure 43).

##### **4.3.4.2 Fracture Pattern**

The typical fracturing pattern in the exposed concrete is illustrated in Figures 44-45. As shown, the predominant pattern is breakage along a diagonal (shear) plane. This pattern reportedly provides greater support than a vertical breakage pattern since the fragments retain high internal friction.

##### **4.3.4.3 Steel Debonding**

The RPB equipment was generally very effective in achieving debonding of the reinforcing steel (Figures 46-47). In many places, it appeared that the reinforcing mesh had been broken by the fracturing operation. Indeed, in one seemingly remarkable instance, a steel dowel recovered from the test pit evidently was also fractured.



**Figure 42. Distribution of Particle Sizes on the COS-36 Project**



**Figure 43. Maximum size of Particles on the COS-36 Project**



**Figure 44. Fracturing Along Shear Plane on the COS-36 Project**



**Figure 45. Breakage Along Shear on COS-36 Project**

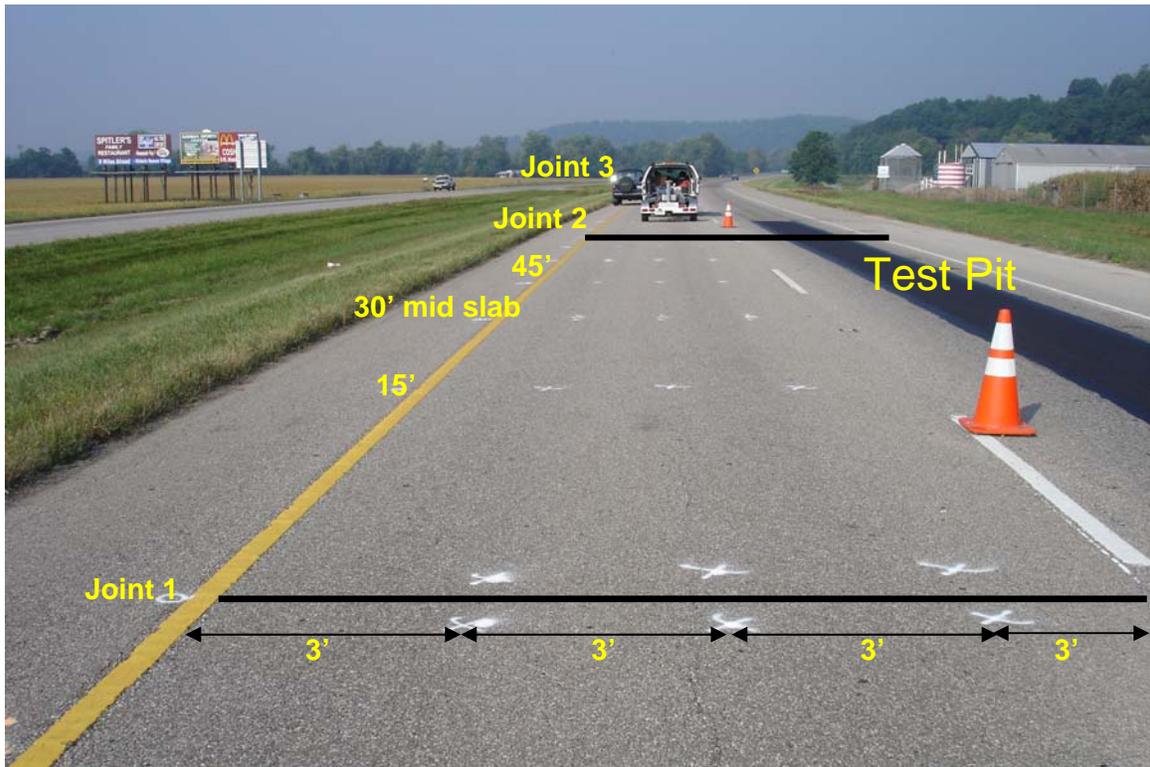


**Figure 46. Debonding of Reinforced Steel on the COS-36 Project**



**Figure 47. Debonding of Reinforcing Steel on the COS-36 Project**

### 4.3.5 Deflection Test Results



**Figure 48. Deflection Observation Points on COS36 Project**

Figure 48 shows FWD deflection observation points. A total of 36 deflection measurements were made at predetermined locations in the lane adjacent to the test pit. The total length of the pavement section considered for deflection measurement is the same as the length of test pit (120'). The length selected corresponds to three underlying joints and two slabs prior to rubblization. At each joint location, three measurements were made on either side. In addition, measurements were made at mid-slab and at quarter points along 3', 6' and 9' from the centerline. The points along 9' and 3' from the centerline correspond to outer and inner wheel paths respectively. The goal of this exploration was to analyze the response of the different pavement layers to FWD loading with special emphasis on the rubblized layer. The analysis would also reflect on the

consistency of the RPB in breaking the concrete slabs. The FWD deflections were analyzed to estimate the in-situ resilient modulus of each layer. A backcalculation analysis was conducted, using *EVERCALC* program. The in-situ modulus of rubblized layer at various locations, along with a plot of maximum deflection values are presented in Figure 49.

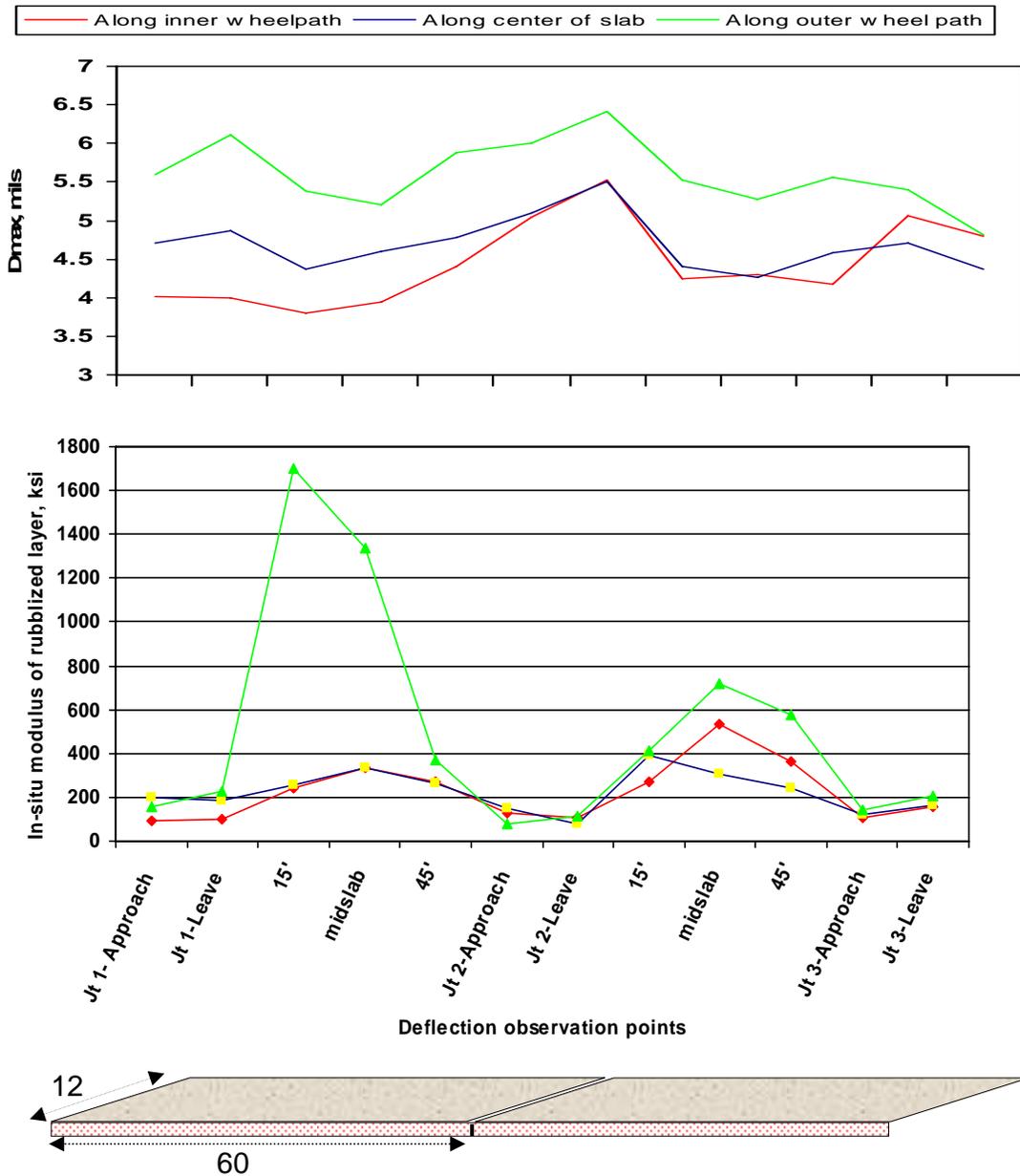


Figure 49. COS36-Variation in  $D_{max}$  and Modulus of Rubblized Layer

The maximum deflection values ranged from 3.8 to 6.42 mils. In general, the maximum deflections follow the expected pattern, with the deflections tending to increase outward from the centerline and closer to the pavement edge. Although maximum deflection can be used to compare the structural condition of two pavements, it does not indicate to what degree each layer is contributing to the surface deflection in a multilayer system. On the other hand, an analysis of the shape of deflection bowl can adequately describe the contribution of each layer and resulting stress conditions in a pavement system. To that effect, the modulus values reflect the structural condition of pavement layers. As seen in figure 49, the range of modulus of rubblized layer is 76ksi to 1700ksi with an average value of 317ksi. At two locations, the modulus values along the outer wheel path were significantly higher than those along inside lines. The residual effect of reinforcement at these locations may have caused an increase in the modulus values. It is interesting to note that, except for these two values, all other data points lie within a narrow range indicating very consistent structural condition of the rubblized layer. The fact that the modulus values along and across the pavement, at and near the joints, all remain within a reasonable limit supports performance claims by RPB.

#### **4.3.6 *The Arkansas Concrete Pavement Rehabilitation Program***

In May 2000, the Arkansas State Highway and Transportation Department (AHTD) began the most ambitious rubblization program undertaken to date, involving rehabilitation of some 356 miles of interstate concrete pavement in 50 projects. The last of those projects were completed in 2005.

Arkansas interstate highways are predominantly 9-10" thick JRCP. Until recently, they were some of the roughest rutting pavements in the country, being rated as the "worst roads" by *Truckers Magazine* due to the extensive faulting at most of the transverse joints. The state's entire interstate system was thus in need of serious rehabilitation.

AHTD concluded that conventional Repair and Overlay or Reconstruction procedures were costly, slow, and/or provided relatively short-term improvements. Consequently, based on reports of promising performance by other agencies and success in construction of two pilot projects in their own state, Arkansas opted to use rubblization plus HMA overlay as the rehabilitation method of choice [19, 20].

At the beginning of their program, Arkansas tested and evaluated both the MHB and RPB equipment. As described below, based on visual observations of the fracture patterns produced in test pit material and deflection measurements, AHTD selected the RPB as the equipment for the total program.

Arkansas R/R specifications [21] require that the rubblized pieces range from sand size to generally 6" or less, the majority pieces being a nominal 1-3", with none more than 8". Three passes with a steel drum vibratory roller were used to settle and smooth the rubblized pieces.

The capabilities of MHB and RPB were evaluated on two test projects in the year 2000 on I-40 in Brinkley and Meniffee townships. At each location, about 2000' long in-service JRCP was rubblized using MHB. An adjacent section of the same length was rubblized using RPB. The fractured layers were seated and overlaid with 9" thick HMA.

As observed on the ODOT test projects, the Arkansas tests indicated that the RPB equipment generally provided smaller particles at the surface of the rubblized layer and throughout the depth of the fractured slab (Figures 50, 51).

Deflection tests were conducted to compare the structural characteristics of the test pavements. The results of the Arkansas deflection testing on outside lanes are plotted in Figures 52 and 53. As shown, the modulus values for the rubblized layer fractured with the RPB are lower and less variable than those produced by the MHB. This result is consistent with the smaller, more uniform particle size observed for the RPB operation.

On the Meniffee project, each of the fracturing techniques produced a rubblized layer whose stiffness was less than the 100ksi threshold value beyond which reflection cracking is expected to occur [9]. On the Brinkley project, however, *all* of the deflection test results on the MHB test section were greater than the 100 ksi threshold, and averaged 175 ksi (Table 3). In contrast, all but one of the measurements on the RPB test sections was less than the critical value, and average 67 ksi.

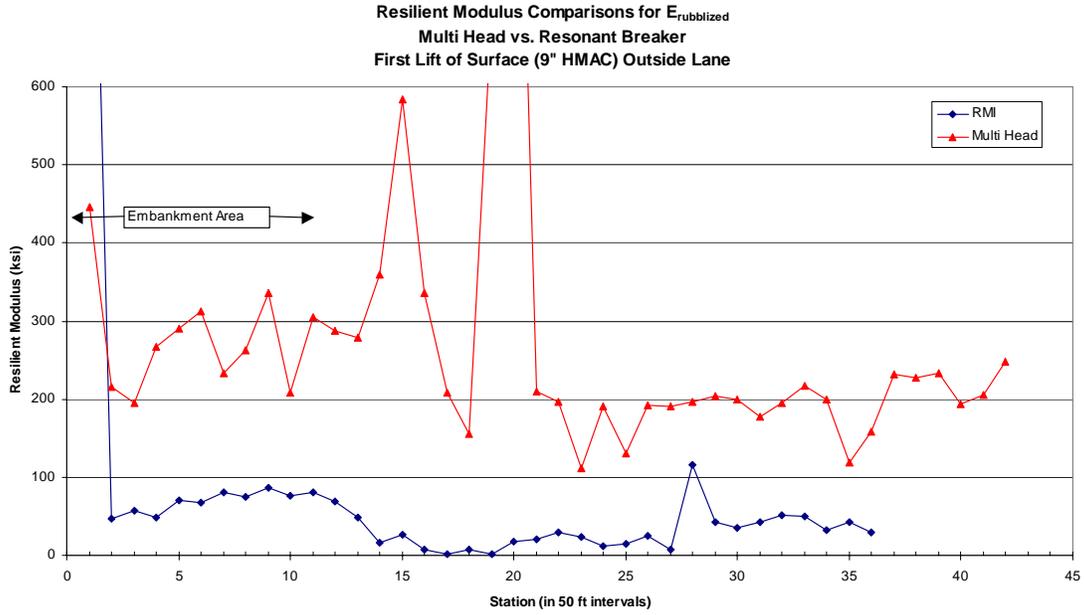
In short, the Arkansas results suggest that while the greater stiffness of the rubblized layer produced by the MHB equipment would generally permit thinner overlays to be used on R/R projects, in at least some cases, the fractured layer would be too stiff to effectively prevent reflection cracking.



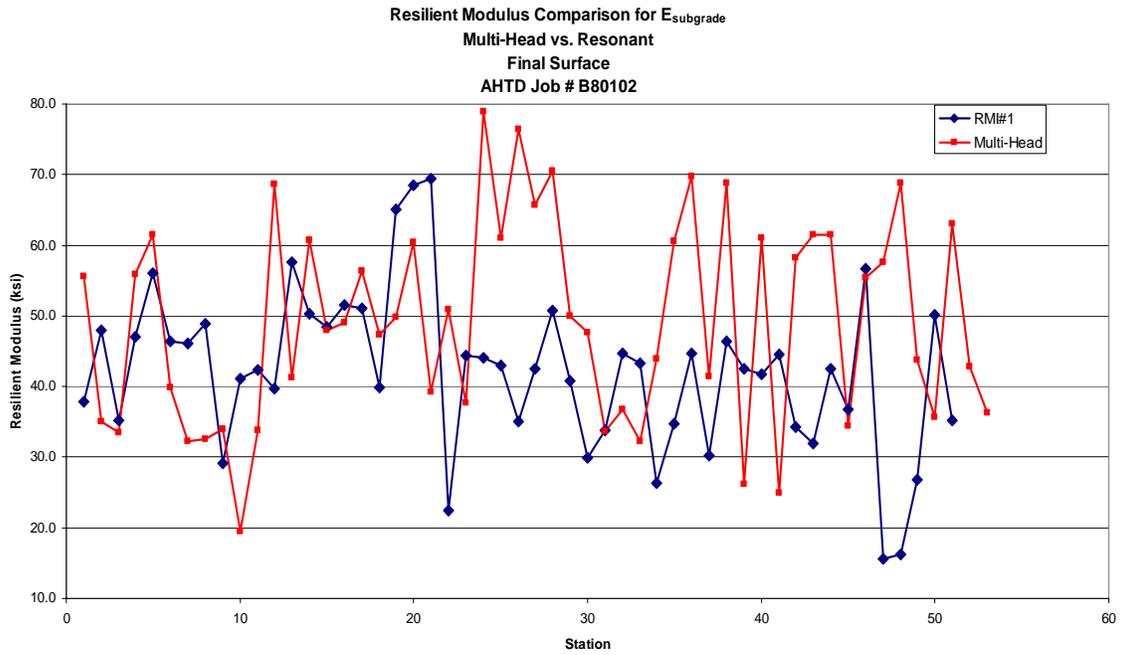
**Figure 50. Distribution of Surface Particles on RPB Project in Arkansas**



**Figure 51. View of Surface Particles on Arkansas MHB Project**



**Figure 52. Comparison of Resilient Modulus values for the Brinkley Project [22]**



**Figure 53. Comparison of Resilient Modulus Values for the Menifee Project [22]**

**Table 3. Average Resilient Modulus Values for Arkansas Test projects**

Project	E rubblized, ksi		E subgrade, ksi	
	RPB	MHB	RPB	MHB
Brinkley	67.2	175.9	6.2	8.6
Meniffee	36.9	51.3	42.3	49.3

**4.3.6 The Alabama Concrete Pavement Rehabilitation Program**

To date, the Alabama Department of Transportation has completed 17 rubblization projects. Recently, the state completed rehabilitation of a significant portion of I-65 south of Montgomery. The existing 10”thick jointed plain concrete pavement, carrying high truck traffic, was in need of major rehabilitation. Alabama’s pavement engineers initially considered various rehabilitation alternatives namely, unbonded concrete overlay, flexible overlay, reconstruction, and rubblized and overlay. Based on a life cycle cost analysis of each alternative, the department concluded that rubblized and overlay alternate was the most cost-effective solution.

Alabama employed RPB to rubblize the existing concrete pavement. In December 2005, the last section of the project was completed and the state hosted a workshop to showcase its rubblization experience. The workshop began with presentations by the department engineers, asphalt industry representatives, the contractors and concluded with a demonstration of the RPB equipment. It was interesting to note that, unlike the case in Arkansas, no formal reports were available to systematically compare the capabilities of different pavement breaking equipment.

However, from the comments made during the workshop, it became evident that the state is extremely satisfied with the operation of RPB and resulting performance of overlays, and efforts are underway to carryout similar projects in the near future.

## **5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS**

### **5.1 Summary**

Crack initiation in composite pavements is generally believed to be caused by vertical and horizontal movements of the slabs. Studies show such movements are directly proportional to the length of the slab. This implies the shorter the length the better the chance of reducing crack development and in turn reflection cracking. Fracturing concrete slabs, which includes cracking and seating (C/S), breaking and seating (B/S) and rubblization, prior to the construction of an asphalt overlay is a method adopted by several states to minimize the problem of reflection cracking. In 1992, ODOT initiated a research program to systematically investigate the effectiveness of fracturing concrete slabs on the performance of AC overlays, in their attempt to establish an appropriate rehabilitation strategy for in-service concrete and composite pavements.

As a part of this research program, in 1993, ODOT constructed two composite pavement test sections on SR-4 (each 1.0 mile long) by breaking the concrete slabs into 18" x 18" (45 cm x 45 cm) fragments, followed by an AC overlay. Three control sections of the same length were built at the same time in the adjacent area. During the first two years after AC overlay, nearly 50% of the joints of control sections developed reflection cracking. In 2002, after nine years of service, all the joints of control sections showed reflection cracking. In contrast to this, only about 20% of joints of B/S pavements displayed reflection cracking in 2002. However, in 2004, a significant number of

transverse cracks were observed to have occurred in the B/S pavements. Although it can be argued that the new cracks in the B/S pavements are due to the fatigue of AC layer, the location, shape and nature of these cracks did not subscribe to that argument. By definition, fatigue cracks are a series of interconnected cracks caused by fatigue failure of the HMA surface (or stabilized base) under repeated traffic loading. The new cracks in SR-4 B/S pavements occurred directly over the underlying joints in the concrete layer and hence are typical of joint reflection cracks. While fatigue cracking implies breaking has transformed the pavement into a flexible pavement, reflection cracking indicates retention/restoration of slab action. Hence, an in-depth forensic analysis of the nature and mechanism of the cracking was conducted to determine the implications of this recent cracking on the expected performance and maintenance requirements of future B/S projects.

The pavement breaking operation on the SR-4 project was performed with a pile hammer. Several other types of pavement breakers are now available, including the Multi-Head Breaker (MHB) and Resonant Pavement Breaker (RPB). Performance claims for this competitive equipment include increased production rates and the ability to produce a variety of controlled breaking patterns (hence, permitting pre-overlay fracturing techniques to be used on distressed concrete pavements). To permit ODOT to evaluate the merits of these performance claims –and thus to provide for more informed, cost-effective decisions regarding the type(s) of equipment permitted to be used on future concrete pavement rehabilitation projects--the evaluation of the SR-4 project was expanded to include a comparable assessment of projects constructed with the MHB and RPB equipment.

To accomplish the objectives of the present study, a program of field evaluations was undertaken on the SR-4 project and three other test projects. On two of the latter projects (I-70 in Madison County and I-71 in Fayette County), the MHB equipment was used to break the pavement; on the third project (SR-36 in Coshocton County), the RPB equipment was used. At each test site, a test pit was dug and a visual assessment of the condition of the fractured pavement overlay and subbase/subgrade was made. Measurements were made of the fracturing pattern at the surface of the concrete and gradation tests were performed to determine the particle size distribution at various depths within the fractured slab. On the MHB and RPB projects, deflection tests were performed to determine the effect of the observed breaking patterns on the stiffness of the pavement layers.

To complement the field observations made on ODOT projects, the researchers met with staff of the Arkansas DOT to discuss their experience with the MHB and RPB equipment gained as part of a monumental (\$1.3 billion, 360 centerline mile) five-year concrete pavement rehabilitation program now nearing completion in that state.

## **5.2 Conclusions and Recommendations**

- Examination of test pit material indicated that the pile hammer used in constructing the B/S sections on the SR-4 project did not consistently provide the vertical through cracking and steel debonding required by the project specifications. As a result, the steel continued to serve its original function of holding the cracks together. Probably some movement is taking place at these cracks, but they are small enough to not exceed the critical strain in the AC. However, the joints continued to move, although at a smaller rate because some

of the movement is taking place at the cracks. Therefore, the reflective cracking is delayed when compared to a composite pavement. Despite this, the overlay on the B/S section provided vastly superior reflection crack performance than the untreated control section. Thus, break and seat still appears to be a viable technique for retarding reflection cracks in overlays of Ohio's jointed reinforced concrete pavement.

- The MHB equipment generally appears capable of consistently providing the breaking patterns and particle sizes required for B/S projects. Use of the MHB on ODOT rubblization projects is more problematic: in the studied sample of projects, not all contractors using this equipment provided the desired results. A more extensive sampling is thus required to definitively establish the suitability of the MHB equipment for rubblization.
- The RPB equipment appears capable of providing the fractured particle size distribution and steel debonding required by ODOT specifications. However, on the COS-36 project, meeting those specifications *retarded--* but did not *prevent--* the subsequent occurrence of reflection cracking. A more extensive sampling is thus required to assess the adequacy of the current rubblize specifications.
- Improvements in ODOT's specifications for fractured slab techniques are needed. On all types of fracturing projects, the quality control requirements need to be modified to require that test pits be more frequently used to ensure that the specified particle size distributions are in fact being achieved throughout the depth of the slab. On rubblize projects, the present particle size distribution

requirements need to be re-examined to ensure that the fracturing operation will avoid, not merely delay, reflection cracking in the subsequent overlay.

### **5.3 Implementation Potential**

- Needed specification changes to provide improved quality assurance on fractured slab projects can be achieved by requiring test pits to ensure that the specified particle size distributions being produced throughout the depth of the slab are in conformity with ODOT specifications. Determining the specifics of any needed changes in the particle size distribution requirements of the rubblization specification will require further, in-depth research.
- A definitive determination of the suitability of the MHB equipment for use on ODOT rubblize projects will require further research.

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### DYNAMIC CONE PENETROMETER Testing on SR4

Three locations within the test pit on SR-4 were selected for DCP testing. The tests were conducted on the subbase and subgrade layers. Penetration readings were taken with each blow of the drop weight. Testing ceased when the penetration depth for each blow was less than 1 mm or the cumulative penetration depth approached one meter.

Plots of penetration versus a corresponding number of blows were generated for each of the DCP test location. The results are presented in the figure below:

